Preparedness for the Long-Term Management of Contaminated Freshwater Bodies and Catchments.
A Decision making exercise with the MOIRA system

Eduardo Gallego[a*], Miguel Magán[a], Miguel Calvín[b], Eugenio Gil[b], Luigi Monte[c], Dmitry Hofman[d]

[a]Universidad Politécnica de Madrid, Nuclear Engineering Department,
José Gutierrez Abascal, 2, E-28006, Madrid, Spain.

[b]Nuclear Safety Council, General Subdirection for Emergencies,
Justo Dorado, 11, 28040 Madrid (Spain)

[c]ENEA, CR Casaccia, via P. Anguillarese, 301, CP 2400, 00100 Roma AD (Italy)

[d]Consult, O. Kyrkogatan 35, Nyköping 61133, Sweden (Sweden)

Abstract. In the mid-long-term after a nuclear accident, the contamination of drinking water sources, fish and other aquatic foodstuffs, irrigation supplies and people's exposure during recreational activities may create considerable public concern, even though dose assessment may in certain situations indicate lesser importance than for other sources, as clearly experienced in the aftermath of accidents like Chernobyl. The MOIRA system is designed to allow for a reliable assessment of the long-term evolution of the radiological situation and of possible alternative rehabilitation strategies, including an objective evaluation of their social, economic and ecological impacts in a rational and comprehensive manner. MOIRA also features a decision analysis methodology, making use of multi-attribute analysis, which can take into account the preferences and needs of different types of stakeholders. A decision-making exercise regarding such problems, in which MOIRA has been be used as a decision support tool, was organised in Spain involving the organizations responsible for emergency management and the affected services, as well as local and regional stakeholders and several international observers. The system resulted very helpful in assessing the overall situation and the alternative management strategies and also facilitated the interaction between agencies which reached a better common understanding of all related issues.

KEYWORDS: Post-accident management, MOIRA system, long-term contamination, freshwater contamination, decision making.

1. Introduction

A decision-making exercise regarding the long-term management of contaminated freshwater bodies and catchments was organised in Spain, in the frame of the Nuclear Safety Council (CSN) Annual Exercises and Simulations Program 2007. This was the first time that the CSN organized an exercise on decision-making in case of contamination of large water bodies. It was also a unique opportunity to test in a fully realistic environment the capabilities of the MOIRA system as a decision support tool, which was one of the demonstration activities included in the EURANOS Project of the 6th Euratom Framework Research Programme (EFRP).

The exercise featured the participation of the organizations responsible for emergency management and the affected services, as well as local and regional stakeholders and several international observers (see Table 1).

* Presenting author, E-mail: eduardo.gallego@upm.es

Table 1: Stakeholders and observers participating in the exercise

Stakeholders involved in the exercise	Observers invited to attend the exercise
• CSN authorities: Staff from Emergencies and Radiological Protection of the Public departments. • Ministry of Environment: General Commissary of the Tagus Water Administration Authority and technical advisors. • Ministry of Interior: Civil Protection and Guardia Civil representatives • Autonomous Government of the region: Regional Government of Extremadura: Counsellor of Environment and technical advisors. • Central Government representatives: Sub-delegation of the Government in Extremadura region representatives (decision-makers in nuclear emergencies). • Water Management Company: Canal de Isabel II representative (water supply for human consumption in Caceres city, public company).	• University of Extremadura and University of the Basque Country: Scientist advisors on determination of environmental radioactivity and its effects. • Ciemat: Staff from the Unit on Research on Radiological Protection of the Public. • Ministry of Defence: Military Unit of Emergencies representative. • ENRESA (National Radioactive Waste Management Company) representative. • International observers: – NRPA (Norway), – RPII (Ireland), – IA-NUTEM (Portugal), – NIPNE (Romania), – ENEA (Italy).

2. The MOIRA Decision Support System

The MOIRA system is a user-friendly decision support tool for analysing management strategies to freshwater systems contaminated by radioactive substances. It was developed and tested during the IV EFRP [1-2] and subject to additional testing and comparisons with other models inside the EVANET-HYDRA network of the V EFRP [3]. Latest version, MOIRA-PLUS© [4], incorporated many features derived from user's experience and feedback. It is a software tool showing a high degree of complexity aimed at assessing the long-term evolution of the radiological situation and the overall effectiveness of countermeasure strategies applied to contaminated freshwater ecosystems by running quantitative evaluations, simulating the consequences of selected interventions, calculating costs and analysing benefits. It organises and structures the knowledge of experts and allows decision makers to use models appropriate for different environmental, social and economic situations and for a specific contamination scenario. The system offers a quick insight in the effectiveness of countermeasures avoiding the implementation of inappropriate and expensive strategies.

MOIRA is intended to be:

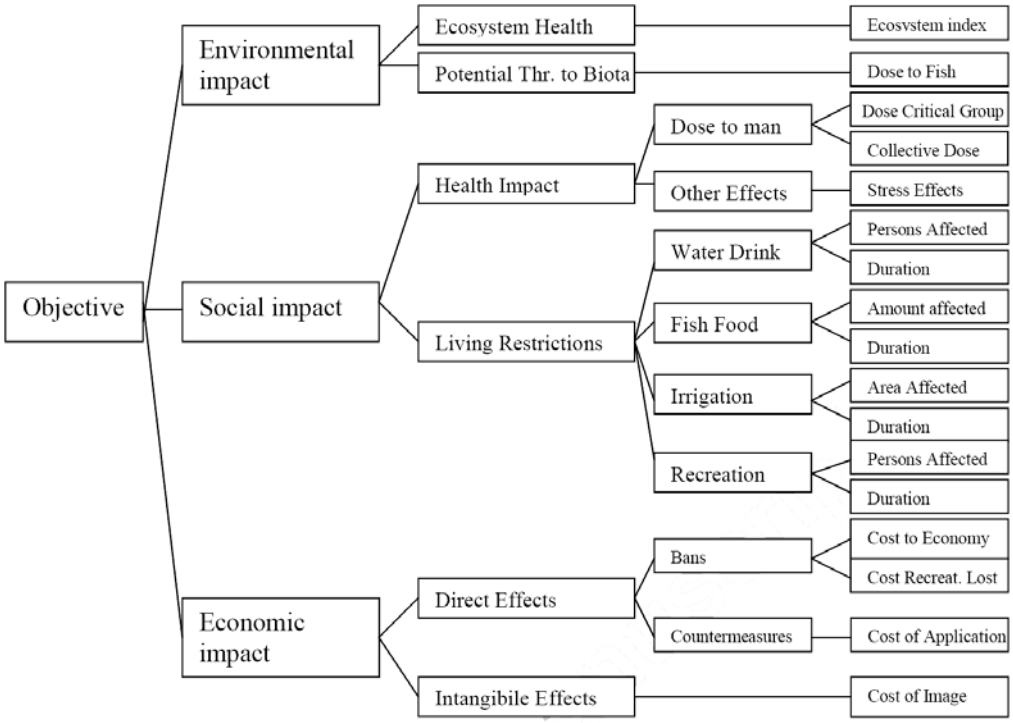
- synthetic, that is knowledge is included and processed in the system in a structured manner,
- accessible, so that the information in the system can be found and used simply and rapidly,
- flexible and extensible, so that new knowledge and models can be included as they become available,
- practical, in the sense that many different types of predictive models can be easily run by non-experts.

MOIRA is based on:

a) Validated models to evaluate the behaviour of radionuclides (^{137}Cs and ^{90}Sr) in contaminated water bodies and biota and to assess the effect of countermeasures on contamination levels.
b) Models to assess the radiation dose to people and biota (fish) by relevant exposure pathways, the effect of countermeasures, and the associated economic impact.
c) A Multi-Attribute value Analysis (MAA) module to evaluate the effectiveness of different countermeasure strategies by accounting for the social, ecological and economic detriments and costs in relation to their benefits.
d) A software system consisting of: 1) software realization of the mathematical models; 2) a GIS (Geographic Information System) and associated databases to select the aquatic system of interest and, if necessary, the default environmental data required to run the models; 3) a graphical user interface; 4) an operating system connecting all the above parts.

MOIRA incorporates social and economic impacts into its MAA frame [5-6] that allows considering social impact measures without converting them into monetary units. On the other hand, the economic costs of the different kinds of countermeasures implemented in the MOIRA sub-models are calculated by using a conceptually simple micro-economic approach, which gives the user a full control on the basic data needed for the calculations (unitary costs and discount rate). Fig.1 displays the tree of objectives considered.

Figure 1: Tree of objectives considered for MAA in the MOIRA system: The overall objective is to minimise the ecological, social and economic impact; each of them is split into different sub-objectives. At the lowest level the objectives can be measured in terms of attributes that are quantified with the system models.



3. Objectives of the exercise

The main objective of the decision-making exercise was "to foster communication and interaction between different cooperating agencies involved in the decision-making process in case of radioactive contamination of water bodies or catchments".

On its side, within the EURANOS project, the demonstration activity on MOIRA aimed to test the applicability of the MOIRA system for the definition and analysis of a variety of appropriate strategies for the long-term management of contaminated freshwater bodies, for both lakes (local scale) and rivers (regional scale), as well as the validity of the system as a tool in the decision making process able to incorporate inputs from different ranges of stakeholders.

A complementary objective was to have the MOIRA system fully operative in an operational emergency response centre, getting useful feedback from operators and users.

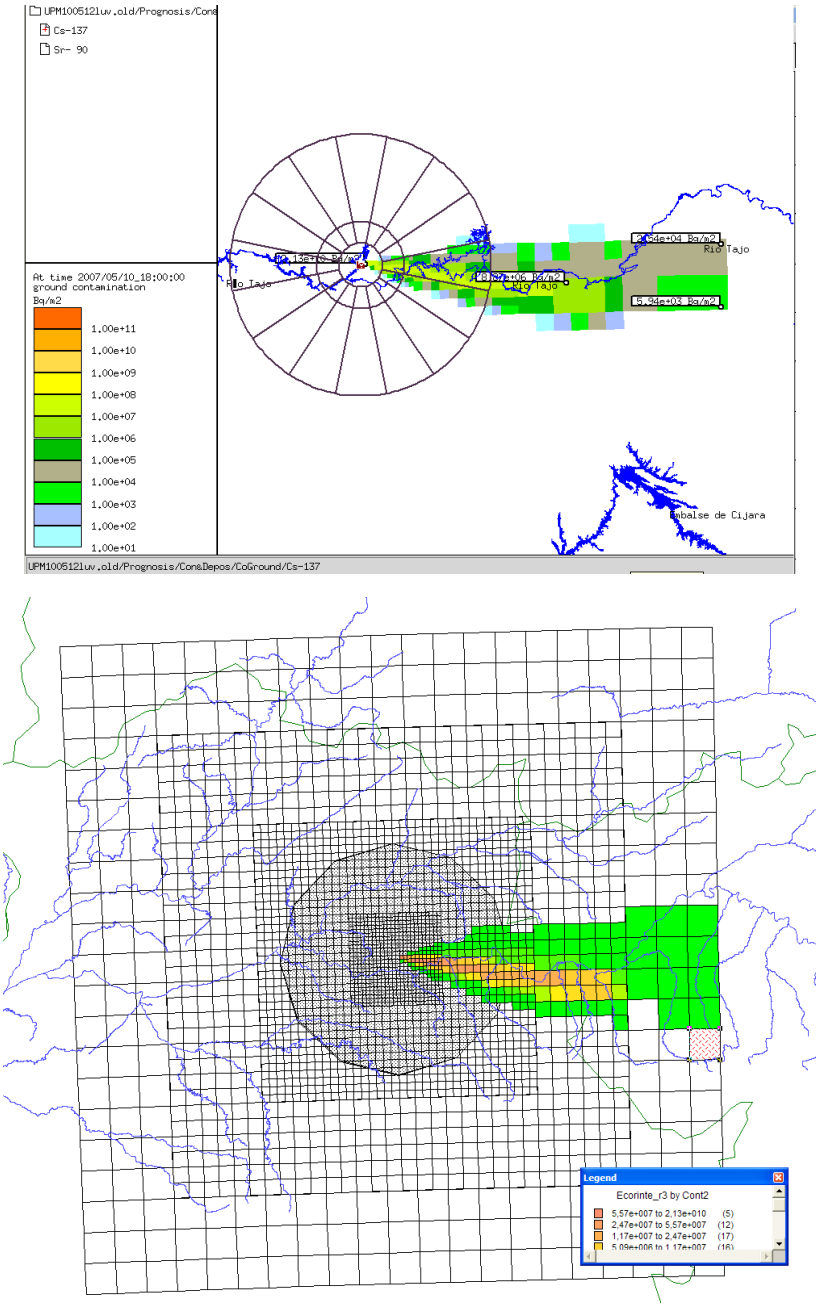
Therefore, both activities fitted perfectly and the decision-making exercise organised by CSN provided the ideal framework for testing the MOIRA system.

4. Scenarios analysed

The exercise was focused in the mid and long-term radiological consequences, as well as in the different alternatives to manage the post-emergency situation in the water contamination-affected area. The endpoints were the radiological recommendations to be given to the authorities in charge of water supply in the contaminated zone, and the decision-making on their side.

A simulation of the contamination resulting from a severe accident leading to significant releases of ^{137}Cs and ^{90}Sr (3% and 0.6% of the reactor inventory respectively) was performed with the RODOS system, and the resulting map of contamination was transferred to the MOIRA system with the help of an ad-hoc developed tool (see Fig. 2).

Figure 2: ^{137}Cs deposited on ground as calculated with the RODOS system for weather conditions with rain (upper figure), and once imported by MOIRA and visualized in the MOIRA GIS (lower figure). The different squares correspond to the calculation grid of RODOS. The largest side of the calculation domain is 160 km.

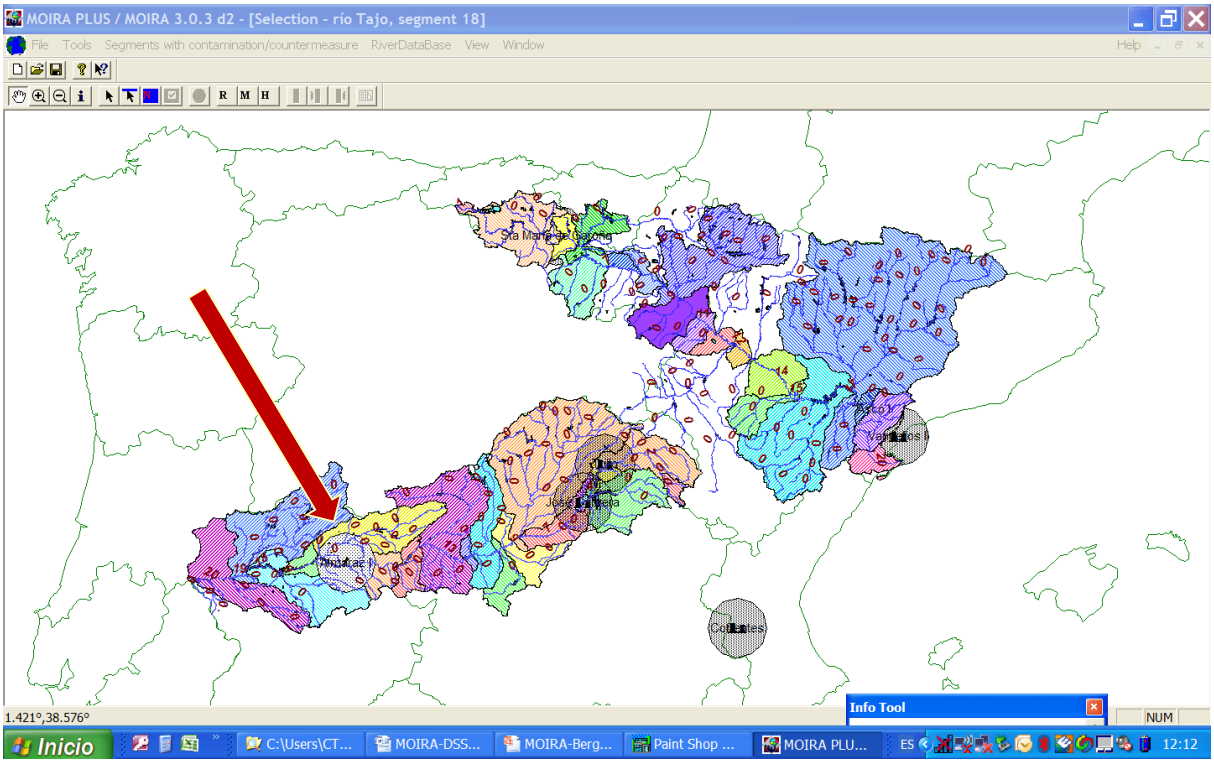


Two specific scenarios in the contaminated area were analysed:

- The first was focused on the contamination of a group of small lakes (local scale). In this scenario, the individual dose for the most exposed individuals was the main concern, with local fishermen being the critical group.
- The second one considered a river basin contamination (regional scale). Usually, these scenarios lead to a reduced individual dose, but affect very large populations, and thus the collective dose may be high. For the exercise, the contamination of part of the Tagus river catchment was considered (Fig. 3). The purpose was to show MOIRA's suitability to study the problem of dragged contamination due to run-off in the river water, thus reaching river sections not directly contaminated by fallout from the radioactive cloud. Due to this contamination drag, which may last for many years, usage of water or fish intake in places far from the accident could constitute an exposure pathway of the population, so there is a need to evaluate the scale of the problem and the feasibility of countermeasures aimed at reducing the dose to population.

Previously to the exercise, a full customisation of the different MOIRA data sets and GIS thematic maps was performed to guarantee the representativeness of the details with regard to land and water uses. The morphological characteristics of lakes and rivers of the region were incorporated. The estimations of run-off and withdrawal from rivers reproduce the mean hydrological behaviour based on historical records (about 30 years) with good accuracy.

Figure 3: Screen of the MOIRA-GIS showing the sub-divisions of the Tagus and Ebro rivers catchments and their main streams within the Spanish territory in different sub-catchments / segments. The exercise was based on the contamination of the Tagus catchment.



5. Results and discussion

5.1 Small lakes scenario

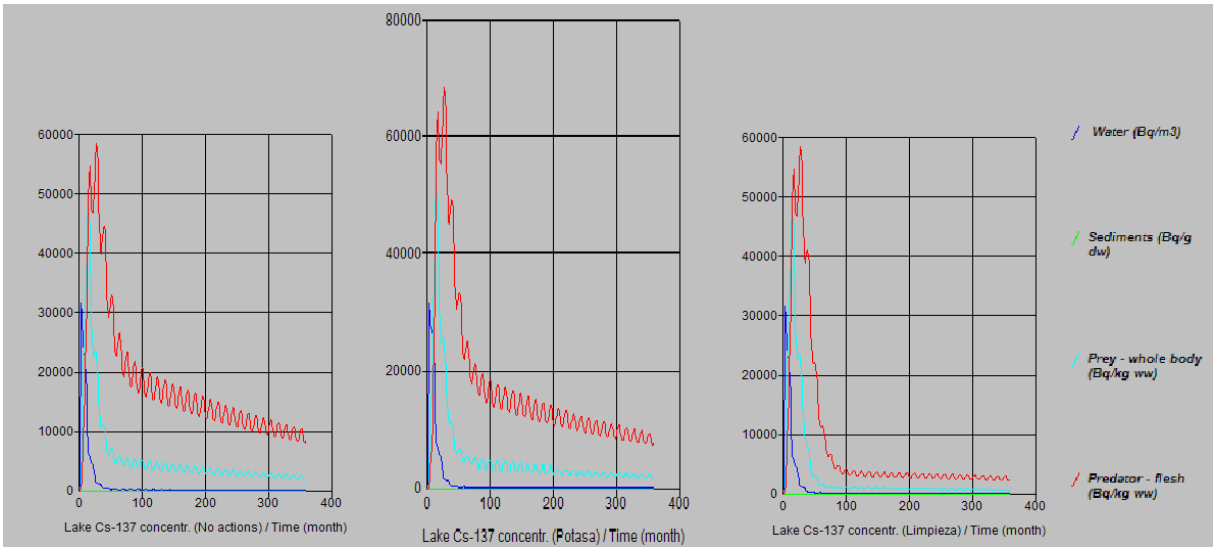
In the case of the small lakes, fish ingestion was considered the main concern. These lakes are in an environmentally protected area, and water is not used neither to irrigate crops nor for human

consumption. Recreational fishing is the main activity that could lead to significant human exposure. Concentrations of both ^{137}Cs and ^{90}Sr in water get down quickly. However, the contamination levels in fish and sediments can remain rather high for many years. Even after 30 years, predicted fish contamination was of the order of 3000 Bq/kg of ^{137}Cs for prey fish and 10000 Bq/kg for predators. The dose to a critical individual was assessed to be well above 1 mSv/y (5.6 mSv in the first year; 45.3 mSv/y total in 30 years). Thus, some action was warranted.

MOIRA was used to simulate the effect on fish contamination and dose reduction of different chemical countermeasures (potassium addition, lake and catchment liming, fertilization). However, none of them was able to significantly improve the situation, due to the short water retention time in the lakes. This is in agreement with actual experience. A physical removal of the lake sediments resulted more effective to reduce fish contamination and doses. It achieved a reduction in contamination and doses of about 60%, but there were several drawbacks associated, the high assessed costs (of the order of 3M€) being not the less important. Fig. 4 shows a comparison (for ^{137}Cs) of the concentration levels predicted by the system in case of natural evolution, compared to potash addition and sediment removal.

Finally, after discussion, the consensus was obtained on the need of implementing a fishing ban or a fish ingestion ban in the area as the only efficient measure. Obviously, the practical perspectives of that option were discussed during the exercise by the relevant regional authorities who should be responsible for its implementation.

Figure 4: Time evolution of ^{137}Cs concentrations in predator and prey fish (Bq·kg^{-1} ww), sediments (Bq·g^{-1} dw) and water (Bq·m^{-3}). Three alternative scenarios are shown: no intervention or "natural" evolution (left); after a 10t potash treatment in month 5th after the contamination event (center); and with a total clean-up of the sediments affecting the upper 10cm layer in month 30th (right).



5.2 River scenario

This part of the exercise was focused in several sectors of the Tagus River downstream from the fallout affected zone to the Portugal border. This is a regulated chain of hyper-annual reservoirs with different uses depending on the sector. Water is used for crop irrigation in well defined areas, supply of drinking water to towns and cities (the main being the city of Cáceres, with about 80,000 inhabitants) and recreational use due to the existence of a natural park in the region.

The affected amount of crops, water, and livestock products is a paramount factor in the assessment of collective doses. Also, the accurate representation of the actual land use in the MOIRA GIS database was considered essential by the implicated agencies to give the assessment a real value.

A summary of the radiological importance of the situation is presented in Fig. 5 and Table 2. Collective dose by ingestion of crops is in general fairly small due to the characteristics of the agricultural production of the region, with a high fraction of the irrigated land devoted to tobacco and forage and low area to crops intended for direct human consumption. Thus, the dominating pathways are, depending on the river sector, the ingestion of fish (which are contaminated with a few $kBq \cdot kg^{-1}$, depending on the season), the external exposure to sediments, the ingestion of livestock products and water.

Figure 5: Collective and individual effective dose assessed for the first year and a 30 year period at different river segments downstream of the directly contaminated area.

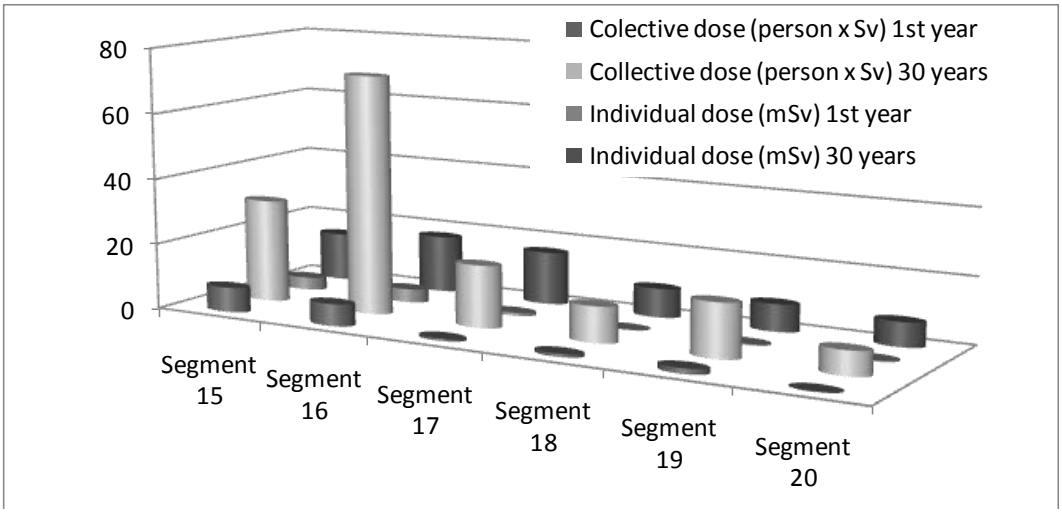


Table 2: Segment 16. Contribution of the different exposure pathways to the most exposed individual (teenager) and collective dose in the first year after the accident and in a 30 years period.

Dose components	Dose to the most exposed individual (mSv)		Collective Dose (person x Sv)	
	1st year	30 years	1st year	30 years
External exposure	0.032	0,712	2.88	56,8
Dose by ingestion of drinking water	0,084	0,264	0	0
Dose by fish ingestion	2.57	10.1	1.56	5.79
Dose by crop ingestion	0.093	0.368	0.05	0,848
Dose by ingestion of livestock products	1.28	5.96	2.14	9.14
Total ingestion dose	4,03	16.7	3.75	15.8
Total Dose	4,06	17,4	6.63	72.5
Total dose caused by ^{137}Cs			1.52	63.6
Total dose caused by ^{90}Sr			5.11	8.92

Water contamination showed a strong seasonal dependency, because in the dry season (May to October) precipitation is very scarce, thus also reducing the runoff of radionuclides from the catchment to the water. The cleanup effect by water coming from upper segments of the river also dilutes the contamination in the water. This effect is more pronounced in the case of ^{90}Sr, due to the non-linearity of its behaviour with respect to runoff intensity, as well as the Sr precipitation under

basic pH conditions which are typical during the summer . Contamination of sediments implies a reload of contaminants in water in the long-term. It increases continuously, even after 30 years, for ^{137}Cs while, for ^{90}Sr, remains almost stable. These effects are depending on the characteristics of each reservoir.

Management alternatives were discussed with the participants at the exercise: fish ingestion ban, treatment of drinking water and sediment removal could indeed be effective at reducing doses or contamination. However, the feasibility of the latter in a large reservoir was, according to the water management authority, very doubtful and its cost very uncertain. Also, in some places, sand from the river bed is extracted for using it in construction industries; its contamination could origin exposure pathways not considered in MOIRA, with a potential economic impact in case of banning that use that should be modelled.

6. Conclusions

The whole exercise was very successful and provided several useful lessons and conclusions. Some of them are related to the MOIRA system and technical issues while others refer to organizational and preparedness aspects against radiological contamination events.

Concerning MOIRA, it was proven to be a mature system, user friendly and relatively easy to set up. It can help to reassure the public by enabling a realistic evaluation of the social, economical, and ecological impact of possible recovery strategies. It clearly can aid cross-agency interaction and thus better common understanding of all related issues. It could also assist in the identification of water bodies where higher levels of contamination might be expected and in the definition of sampling strategy.

However, the proper implementation of MOIRA requires that a lot of background environmental and socio-economic data is collected. Successful operational use may require that data is prepared ahead and maintained over time. Although definition of generic typical environments can be useful to get generic results, site specific peculiarities can be relevant to obtain representative results, which otherwise could be dismissed by local stakeholders and intervening agencies. For example, the exact location and capacity of points at which drinking water is extracted. In Spain some work is still required to adequately represent the existing lakes and some rivers. Some advances have been made regarding crop information. Ideally, this will allow MOIRA to automatically estimate crop productions from GIS data in future versions.

The capacity to assess the economic cost of implementing countermeasures was considered a very positive characteristic of MOIRA. However, base unit costs should be reviewed taking into account local specific information if available.

The system should also have models to assess the dose to workers implementing countermeasures, at least those implying a higher contact with contaminated material, like sediments.

The exercise unveiled the need of a better interface and understanding between agencies and stakeholders and allowed all participants to have a more detailed knowledge of their respective competencies and capacities, as well as of their counterparts. The use of MOIRA allowed them to get a very close idea of the magnitude of the expected problem. This can raise awareness and knowledge among stakeholders, and prepare plans for certain countermeasures. Some opportunities for future collaboration between CSN and water management authorities and regional governments were identified. Both observers and stakeholders agreed that MOIRA proved to be a helpful tool for decision-making in kind of scenarios.

One open point was the management of such a crisis from a psychological and sociological point of view. It was recognized that the circumstances of the resulting social crisis can strongly influence the decision-taking in a real situation. For instance: how to communicate that drinking water is not a

critical exposure pathway? Obviously, an assessment tool like MOIRA seems necessary to put the different issues in their right perspective.

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